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ANALYSIS

Non-parametric frontier approach to modelling the relationships among population, GDP, energy consumption and CO₂ emissions

Sebastián Lozano*, Ester Gutiérrez

University of Seville, E.S.I., Department of Industrial Management, Camino de los Descubrimientos, s/n, 41092 Sevilla, Spain

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ABSTRACT

In this paper, a non-parametric approach based in Data Envelopment Analysis (DEA) is proposed as an alternative to the Kaya identity (a.k.a ImPACT). This Frontier Method identifies and extends existing best practices. Population and GDP are considered as input and output, respectively. Both primary energy consumption and Greenhouse Gas (GHG) emissions are considered as undesirable outputs. Several Linear Programming models are formulated with different aims, namely: a) determine efficiency levels, b) estimate maximum GDP compatible with given levels of population, energy intensity and carbonization intensity, and c) estimate the minimum level of GHG emissions compatible with given levels of population, GDP, energy intensity or carbonization index. The United States of America case is used as illustration of the proposed approach.

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1. Introduction and literature review

In the last twenty years a growing concern has been developed about the problem of global warming due to anthropogenic GHG emissions. Although imperfect and not too ambitious, the Kyoto Protocol, signed under the United Nations Framework Convention for Climate Change (UNFCCC), represents a welcome first step in the control of GHG emissions aimed at stabilising GHG concentrations at relatively safe levels. Although there is still much uncertainty about the exact value of the climate sensitivity and of the global temperature increases associated to different concentration pathways, there is no doubt that the environmental, social and economic consequences of the foreseeable climate change can be substantial (e.g. Parry et al., 2001) and that, given the effects delay, urgent action is due. Thus, it has been established that in order to guarantee a mean

global temperature increase below 2°C compared to pre-industrial levels, the current trend of GHG emissions increase must be reversed by 2020, GHG emissions in 2050 must be half of those in 1990 and in 2100 one fifth of those of 1990 (e.g. Kulessa, 2007). That is a very tall order indeed, especially given continuing population and economic growth.

There have been a number of studies aimed at analysing the factor that influence GHG emissions. According to the IPAT approach (Ehrlich and Holdren, 1970, 1972; Commoner, 1971), the main drivers of environmental degradation are Population (P), Affluence (A) and Technology (T). The T component is, by definition, the environmental impact per unit of economic activity. IPAT is a generic tool to analyse environmental impacts, not just GHG emissions, and can be used at different levels (e.g. MacKellar et al., 1995; DeHart and Soulé, 2000). In the case of GHG emissions, a variant called

* Corresponding author. Tel.: +34 954487208; fax: +34 954487329.

E-mail address: slozano@us.es (S. Lozano).

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ImPACT, that adds Consumption (C) as a driver, has been proposed (Waggoner and Ausubel, 2002). In the usual case that A is measured using Gross Domestic Product (GDP) per capita and C corresponds to Energy consumption, ImPACT coincides with the so-called Kaya identity (Kaya, 1990; Yamaji et al., 1991), which can be formulated by the simple equation

$$CO_2 = P \cdot \frac{GDP}{P} \cdot \frac{Energy}{GDP} \cdot \frac{CO_2}{Energy} \quad (1)$$

where CO_2 represents CO_2 emissions and Energy represents primary energy consumption. Eliminating P from (1) and rewriting it as

$$\frac{CO_2}{GDP} = \frac{Energy}{GDP} \cdot \frac{CO_2}{Energy} \quad (2)$$

the Kaya identity can also be used to measure the influences of energy intensity (i.e. $Energy/GDP$) and carbonization index ($CO_2/energy$) on the emission intensity (CO_2/GDP) (Milenik and Goldemberg, 1999; Roca and Alcántara, 2001, 2002). Similarly, eliminating Energy from (1) and rewriting it as

$$\frac{CO_2}{P} = \frac{GDP}{P} \cdot \frac{CO_2}{GDP} \quad (3)$$

the influence of GDP per capita and emissions intensity on emissions per capita can also be analyzed.

The Kaya identity approach is also related to the flexible and useful decomposition analysis approach. Thus, for example, Zhang (2000) used the following equation

$$CO_2 = P \cdot \frac{GDP}{P} \cdot \frac{Final\ Energy}{GDP} \cdot \frac{Primary\ Energy}{Final\ Energy} \cdot \frac{Fossil\ Fuel}{Primary\ Energy} \cdot \frac{CO_2}{Fossil\ Fuel} \quad (4)$$

which takes into account not only the population, economic growth and energy intensity effects but also the primary to final conversion factor, the fossil fuel energy component and the fossil fuel carbon mix. Time-series decomposition analyses of CO_2 emissions have been made for a single country (e.g. Zhang, 2000; Wang et al., 2005) or for a group of countries (e.g. Hamilton and Turton, 2002). The decomposition can also include the different economic sectors (e.g. Paul and Bhattacharya, 2004) and does not necessarily include the Population factor (e.g. Sun, 1999). Cross-sectional decomposition analysis allows for comparing the influence of the factors on the differences on total or per capita CO_2 emissions of different regions or groups of countries (e.e. Ang and Zhang, 1999; Lee and Oh, 2006).

The IPAT-ImPACT-Kaya approach is flexible, quite parsimonious and rather easy to use. It allows an explanatory analysis of the relative influence of the different factors in the level of emissions and its variation between time periods. It can also be used to forecast future CO_2 emissions levels when all the factors considered are known. However, this approach has limitations. One is that it is just a multiplicative identity and, as such, although it always holds, assumes proportionality between the effects of the different factors *ceteris paribus*. This limitation led to the development of a stochastic version of IPAT known as STIRPAT (STochastic Impacts by Regression on Population, Affluence and Technology, Dietz and Rosa, 1994), that basically considers the following model

$$I_i = a \cdot P_i^b \cdot A_i^c \cdot e_i \quad (5)$$

where parameter a represents a multiplicative constant, subscript i indicates that the corresponding magnitude varies across observational units, Technology is modelled as a the residual term e_i and the exponents b and c , called respectively Population Elasticity of Impact and Affluence Elasticity of Impact, are estimated by Optimal Least Squares (OLS) regression. Examples of the use of STIRPAT to analyze CO_2 emissions are Dietz and Rosa (1997), Shi (2003), York et al. (2003) and Fan et al. (2006).

Although the STIRPAT approach can get very interesting results about the influences of the population and affluence factors as well as of other factors that may be included (see e.g. York et al., 2005; Scholz, 2006), it is a parametric approach and since it is based on regression, it measures central tendencies. On the contrary, in this paper, we propose a non-parametric Frontier Method (FM). A FM works through the identification of the Efficient Frontier of an underlying Production Function. The Efficient Frontier is determined by those observations that are non-dominated along the input and output dimensions considered and represent the Best Practices. While regression has an explanatory character, FM is normative, i.e. any given operation point can be projected onto the Efficient Frontier and improved target values for the inputs and outputs be computed. Thus, while the Kaya identity can be seen as a rigid equation that always holds by definition, the proposed approach considers a whole feasible operating region built from the observed data and for which an efficient frontier can be computed. Moreover, insofar as this feasible operating region is built in a non-parametric fashion, the approach is less vulnerable to misspecification errors than STIRPAT, for example. It is also true that FM lacks the modelling flexibility of regression-based approaches but its best-practices character provides a better benchmark than the average behaviour estimated with OLS regression. On the other hand, the Kaya identity can be more useful, in conjunction with decomposition analysis, for assessing the relative contribution of the different factors (including structural changes in the economic activity) on the corresponding change in emissions.

FM has been previously used to estimate foregone GDP due to a forced reduction in pollution emissions dictated by quantitative regulatory standards (Zaim and Taskin, 2000a), to compute the minimum amount of CO_2 emissions required to carry out production and the minimum amount of CO_2 emissions without sustaining output congestion (Zofío and Prieto, 2001), to measure environmental efficiencies of countries (Zaim and Taskin, 2000b; Ramanathan, 2002), to identify the implicit environmental strategy followed by different countries (Arcelus and Arocena, 2005), to compute the GDP loss per ton of CO_2 emissions due to environmental regulations (Zhou et al., 2006), to estimate national Total Factor Productivity (TFT) when CO_2 emissions are considered as undesirable outputs (Jeon and Sickles, 2004; Lo et al., 2005; Kumar, 2006), to forecast the links between world energy consumption and CO_2 emissions given world GDP (Ramanathan, 2006), to compute non-radial Malmquist environmental performance index considering CO_2 and three other pollutants (Zhou et al., 2007), to measure the carbon emission performance of eight world regions (Zhou et al., 2008), and to compute country CO_2 emissions entitlements (Gomes and Lins, in press). For more information, refer to Zhou et al. (in press), which present a survey of FM applications in energy and environmental studies.

In this paper, we propose a non-parametric FM approach to modelling the relationships among population, GDP, energy consumption and GHG emissions. In Section 2, several Linear Programming (LP) models are formulated and discussed. In Section 3, some results of the application of the proposed approach, especially for the case of the United States are presented. The last section summarizes and concludes.

2. Proposed approach

In this section we present a number of non-parametric FM models that can be used to compute unknown variables given the other ones. The assumed production function considers P as input, GDP as output and Primary Energy (PE) and GHG emissions as undesirable outputs. Following Färe et al. (1989) the undesirable outputs are considered Weakly Disposable (WD) while for the desirable output GDP Strong Disposability (SD) is assumed. This takes into account the fact that reducing the undesirable outputs (i.e. energy consumption and GHG emissions) may consume divert resources from the production of the desirable output. This treatment of GHG emissions as a WD undesirable output is relatively common and has been considered before in Zaim and Taskin (2000a, 2000b), Zofio and Prieto (2001), Jeon and Sickles (2004), Arcelus and Arocena (2005), Kumar (2006) and Zhou et al. (2006) among others. Treating PE as another undesirable output is a novelty. When energy (sometimes as PE, some others as commercial or final energy consumption) is considered, it is commonly included as an input (Jeon and Sickles, 2004; Kumar, 2006; Zhou et al., 2006), as a SD output (Gomes and Lins, in press) or its fossil fuel component as an input and its non-fossil fuel component as a SD output (Ramanathan, 2002, 2005). We adopt the view that PE is undesirable in the sense that, ceteris paribus, the lower PE the better. We have not considered energy as a SD input because that would imply that energy consumption could be increased without limit and without increasing neither GDP nor GHG emissions (see for example Färe and Grosskopf, 2003). Assuming that energy is WD, the mathematical treatment of that variable in the models, at least in the case of Constant Returns to Scale, would be identical whether it is considered a WD input or a WD undesirable output. The first option would emphasize the view of energy as a necessary resource that the economy needs in order to work. This point of view is obviously correct and, as mentioned above, most DEA studies consider energy as an input. The alternative view of energy as a WD undesirable output has been however adopted to emphasize that energy consumption per se may be undesirable insofar it is not required or does not contribute to increase GDP. In one view, energy is required for GDP; in the other, GDP brings about energy consumption, in addition to GHG emissions.

Since we consider a total of four variables (namely P , GDP, PE and GHG) for the production function, the Efficient Frontier corresponding to the Best-Practice computed from the sample observations will be a non-parametric, piecewise linear approximation of the true Efficient Frontier and represents a certain 3-D surface $f(P, \text{GDP}, \text{PE}, \text{GHG}) = 0$. In the following, we will formulate different mathematical models, all of them LP and, in most cases, consisting in determining one of the variables (unknown) given the values of the other three. When considered con-

venient, the Energy Intensity parameter ($\text{EI} = \text{PE}/\text{GDP}$) can be used as a surrogate of PE and Carbon Intensity ($\text{CI} = \text{GHG}/\text{GDP}$) or Carbonization Factor ($\text{CF} = \text{GHG}/\text{PE}$) as surrogates of GHG.

2.1. Efficiency assessment

Our first model is aimed at determining whether a given observation (labelled 0) is or not efficient. In this model, the values of all four variables are given, i.e. $(P_0, \text{GDP}_0, \text{PE}_0, \text{GHG}_0)$, and the question is whether the observation is efficient or, on the contrary, a dominating operation point can be found producing more desirable output and less undesirable outputs. For this purpose, the model uses a so-called directional distance function (Chung et al., 1997; Färe and Grosskopf, 2004). This consists in choosing a vector, namely $g = (\text{GDP}_0, -\text{PE}_0, -\text{GHG}_0)$, which represents a direction along which the observation is to be projected. Note that the chosen vector has a positive component for the desirable output and negative components for the undesirable outputs. Therefore, any step along this direction is beneficial. The model computes the largest possible step size along this direction. Thus,

$$\begin{aligned} & \text{Max } \beta \\ & \text{s.t.} \\ & \sum_{j=1}^N \lambda_j P_j \leq P_0 \\ & \sum_{j=1}^N \lambda_j \text{GDP}_j \geq \text{GDP}_0 \cdot (1 + \beta) \\ & \sum_{j=1}^N \lambda_j \text{PE}_j = \text{PE}_0 \cdot (1 - \beta) \\ & \sum_{j=1}^N \lambda_j \text{GHG}_j = \text{GHG}_0 \cdot (1 - \beta) \\ & \lambda_j \geq 0 \quad \forall j \quad \beta \geq 0 \end{aligned} \tag{6}$$

where N is the number of observations that form the sample, β is the step size and λ_j are non-negative multipliers that define the target operation point as a linear combination of the sample observations. Note the equality character of the constraints corresponding to the two undesirable outputs. That is due to their WD character.

Model (6) uses a directional distance function approach so that an optimal value $\beta^* > 0$ denotes inefficiency and the larger β^* the greater the inefficiency, i.e. the larger the distance from $(P_0, \text{GDP}_0, \text{PE}_0, \text{GHG}_0)$ to the Efficient Frontier. This is shown in Fig. 1 where the vertical axis represents the good output GDP and the two undesirable outputs are represented in an abstract way by the horizontal axis appropriately labelled u^- . The shaded area corresponds to the production possibility set defined by the sample of observations and the strong (respectively weak) disposability assumption of the desirable (respectively undesirable) outputs. The improvement vector points to the North-West and the computed target operation point F corresponds to the maximum advancement along that direction.

The directional distance function approach is common when undesirable outputs are considered because of its flexibility in choosing the projection direction. Jeon and Sickles (2004), Arcelus and Arocena (2005), Kumar (2006) use this approach. An alternative would be to use a hyperbolic graph efficiency approach such as the one used in Zaim and Taskin (2000a, 2000b) or Zofio

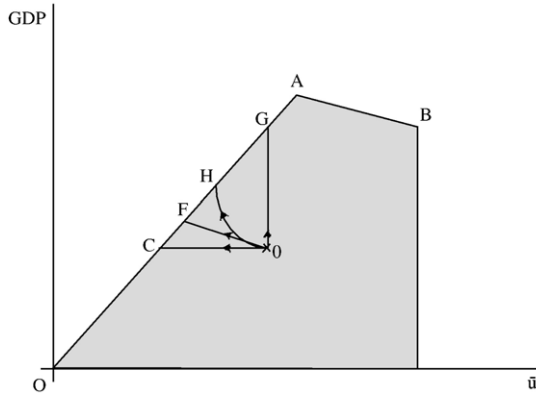


Fig. 1 – Efficiency assessment with directional distance function.

and Prieto (2001) or the mixed environmental performance approach in Zhou et al. (2008). Thus, for example, in Fig. 1, the hyperbolic graph efficiency projection would correspond to point H.

In order to further assess the location of the observations within the production possibility set two additional models can be used. The first one corresponds to using a projection vector $g = (GDP_0, 0, 0)$ and corresponds to the Maximum-GDP-Growth model in Arcelus and Arocena (2005) in contraposition with the Mixed-Growth model which corresponds to model (6) above. Thus, in Fig. 1, model (7) below would project observation 0 onto point G.

$$\begin{aligned}
 &\text{Max } \gamma \\
 &\text{s.t.} \\
 &\sum_{j=1}^N \lambda_j P_j \leq P_0 \\
 &\sum_{j=1}^N \lambda_j GDP_j \geq GDP_0 \cdot (1 + \gamma) \\
 &\sum_{j=1}^N \lambda_j PE_j = PE_0 \\
 &\sum_{j=1}^N \lambda_j GHG_j = GHG_0 \\
 &\lambda_j \geq 0 \quad \forall j \quad \gamma \geq 0.
 \end{aligned} \tag{7}$$

The second model uses as projection vector $g = (0, -PE_0, -GHG_0)$ and corresponds to the undesirable-output-oriented model in Tyteca (1996, 1997) and also to the No-GDP-Growth model in Arcelus and Arocena (2005).

$$\begin{aligned}
 &\text{Max } \alpha \\
 &\text{s.t.} \\
 &\sum_{j=1}^N \lambda_j P_j \leq P_0 \\
 &\sum_{j=1}^N \lambda_j GDP_j \geq GDP_0 \\
 &\sum_{j=1}^N \lambda_j PE_j = PE_0 \cdot (1 - \alpha) \\
 &\sum_{j=1}^N \lambda_j GHG_j = GHG_0 \cdot (1 - \alpha) \\
 &\lambda_j \geq 0 \quad \forall j \quad \alpha \geq 0.
 \end{aligned} \tag{8}$$

In Fig. 1, the projection of observation 0 using model (8) would correspond to point C. Alternatively, instead of a directional distance function as above, a non-radial undesirable-output-oriented model as in Zhou et al. (2007) can be used.

2.2. GDP maximization

The second model we formulate aims at maximizing GDP given the values of the other three variables. Thus, P is known, either PE or EI is known and either GHG or CF is fixed. Therefore, we have some variants of the model. For the sake of simplicity, let us assume that the absolute values of the undesirable outputs are fixed at levels PE and GHG respectively. The other variants of the model are formulated in Appendix A.

$$\begin{aligned}
 &\text{Max } GDP \\
 &\text{s.t.} \\
 &\sum_{j=1}^N \lambda_j P_j \leq P \\
 &\sum_{j=1}^N \lambda_j GDP_j \geq GDP \\
 &\sum_{j=1}^N \lambda_j PE_j = PE \\
 &\sum_{j=1}^N \lambda_j GHG_j = GHG \\
 &\lambda_j \geq 0 \quad \forall j \quad GDP \geq 0.
 \end{aligned} \tag{9}$$

This model allows the estimation of the maximum value of GDP compatible with given values of P , PE and GHG . This is shown in Fig. 2. Fixing the value of the undesirable outputs corresponds to fixing the horizontal coordinate and maximizing GDP corresponds to finding the maximum feasible value along that vertical, i.e. point G. This type of model that concentrate on a subset of the outputs presents some similarities with the output sub-vector measure of technical efficiency as defined in Färe et al. (1994, p. 250). The difference is that the latter evaluates the increase in the selected outputs measured from a specific operating point being assessed, while model (9) computes the maximum value of the output given fixed values of all the other inputs and outputs.

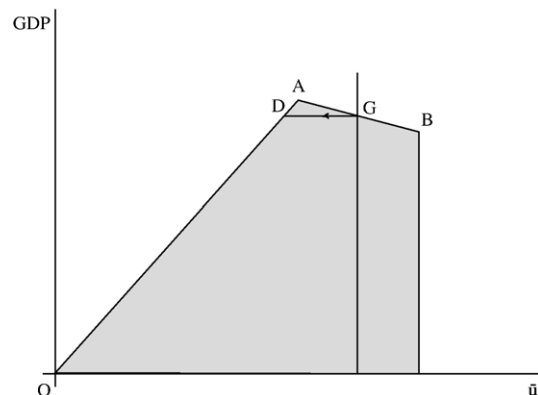


Fig. 2 – GDP maximization fixing the other variables.

Similarly, in spite of the apparent similarities between this model (9) and model (7), model (7) has a different aim and uses different data from those of model (9). Model (7) computes a directional distance-based efficiency measure for any specific observation labelled 0 (note the subindex 0 in the right hand side of the constraints). The direction vector considered in model (7) looks for improvement in all three outputs, both desirable and undesirable, the so-called Mixed-Growth Strategy in Arcelus and Arocena (2005). Although the model computes a benchmark on the efficient frontier (actually only weak efficiency is guaranteed), the emphasis is in measuring the distance to the frontier. In model (9), the data used correspond to target values of P , GHG (or equivalently CF) and PE (or equivalently TEI), and the objective is to determine the maximum GDP attainable given those target values. These values do not need to correspond to any specific observation. Also, the emphasis is on the GDP target, not on computing any hypothetical efficiency measure.

Since as it occurs for example along the segment AB in Fig. 2 it may be possible to reduce undesirable outputs of the target operating point computed by model (9), the following model may be solved as a second phase to find how much the fixed values of the undesirable outputs could be decreased without loss w.r.t. the maximum GDP estimated. In Fig. 2, this radial reduction corresponds to the horizontal line from G to D. Let GDP' the optimal value of the objective function of Eq. (9). Considering PE and GHG as upper bounds, i.e.

maximum allowed values of the undesirable outputs, we can formulate the following model

$$\begin{aligned} &\text{Max } \beta \\ &\text{s.t.} \\ &\sum_{j=1}^N \lambda_j P_j \leq P \\ &\sum_{j=1}^N \lambda_j GDP_j \geq GDP' \\ &\sum_{j=1}^N \lambda_j PE_j = PE \cdot (1 - \beta) \\ &\sum_{j=1}^N \lambda_j GHG_j = GHG \cdot (1 - \beta) \\ &\lambda_j \geq 0 \quad \forall j \quad \beta \geq 0. \end{aligned} \quad (10)$$

This model (10) is similar to model (8) although model (8), using a direction vector that gives preference to the reduction of undesirable outputs (a strategy first proposed by Tyteca, 1996, 1997) is aimed at computing a measure of environmental efficiency for a specific observation whose input and output data appear in the right hand side of the corresponding constraints. On the other hand, model (10) is presented as a way of projecting on the efficient frontier after model (9) has been solved and the reason why such a step may be needed is the fact that operating points lying on the segment AB in Fig. 2 are not efficient because the same output can be obtained with

Table 1 – Efficiency assessment with asymmetric output-oriented directional distance function (in bold optimal β^* values below 0.1)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	
Australia	0.693	0.700	0.696	0.689	0.678	0.681	0.670	0.658	0.593	0.543	0.531	0.487	0.453	0.388	0.335	Australia
Austria	0.137	0.142	0.100	0.101	0.088	0.097	0.100	0.091	0.072	0.055	0.041	0.056	0.060	0.066	0.048	Austria
Belgium	0.319	0.317	0.305	0.302	0.298	0.287	0.285	0.258	0.245	0.220	0.188	0.177	0.165	0.162	0.142	Belgium
Canada	0.646	0.655	0.661	0.660	0.655	0.655	0.659	0.620	0.564	0.486	0.416	0.406	0.376	0.355	0.304	Canada
Czech Republic	0.890	0.896	0.888	0.884	0.876	0.869	0.865	0.869	0.862	0.852	0.854	0.851	0.846	0.847	0.842	Czech Republic
Denmark	0.155	0.185	0.174	0.191	0.162	0.142	0.147	0.143	0.127	0.107	0.077	0.072	0.073	0.064	0.054	Denmark
Finland	0.152	0.194	0.239	0.252	0.244	0.216	0.200	0.164	0.105	0.098	0.054	0.051	0.045	0.011	0.000	Finland
France	0.190	0.206	0.195	0.190	0.174	0.174	0.182	0.164	0.152	0.129	0.110	0.103	0.097	0.096	0.087	France
Germany	0.365	0.314	0.290	0.284	0.261	0.250	0.244	0.226	0.201	0.182	0.154	0.144	0.143	0.145	0.133	Germany
Greece	0.543	0.529	0.530	0.536	0.538	0.534	0.534	0.536	0.538	0.524	0.523	0.509	0.495	0.486	0.472	Greece
Hungary	0.786	0.798	0.786	0.786	0.779	0.776	0.776	0.762	0.748	0.737	0.718	0.712	0.697	0.691	0.675	Hungary
Iceland	0.379	0.369	0.377	0.387	0.369	0.378	0.370	0.371	0.322	0.279	0.241	0.208	0.233	0.208	0.129	Iceland
Ireland	0.494	0.482	0.468	0.466	0.457	0.436	0.402	0.317	0.253	0.199	0.133	0.066	0.000	0.022	0.000	Ireland
Italy	0.051	0.047	0.045	0.049	0.037	0.043	0.037	0.033	0.034	0.025	0.008	0.000	0.001	0.009	0.018	Italy
Japan	0.033	0.027	0.027	0.033	0.052	0.042	0.039	0.033	0.030	0.035	0.027	0.016	0.021	0.000	0.000	Japan
Latvia	0.861	0.861	0.885	0.883	0.863	0.844	0.841	0.818	0.797	0.767	0.730	0.733	0.714	0.693	0.673	Latvia
Netherlands	0.431	0.444	0.436	0.443	0.426	0.417	0.431	0.388	0.351	0.306	0.275	0.279	0.279	0.277	0.296	Netherlands
New Zealand	0.639	0.648	0.652	0.633	0.617	0.606	0.608	0.615	0.605	0.598	0.594	0.589	0.578	0.563	0.548	New Zealand
Norway	0.260	0.209	0.155	0.162	0.150	0.111	0.101	0.070	0.067	0.065	0.030	0.031	0.000	0.010	0.000	Norway
Poland	0.920	0.922	0.920	0.917	0.914	0.906	0.903	0.896	0.882	0.876	0.866	0.864	0.859	0.857	0.851	Poland
Portugal	0.329	0.322	0.307	0.339	0.351	0.343	0.333	0.334	0.335	0.306	0.325	0.329	0.299	0.335	0.317	Portugal
Slovakia	0.843	0.846	0.844	0.835	0.821	0.813	0.804	0.796	0.784	0.781	0.776	0.781	0.767	0.758	0.746	Slovakia
Slovenia	–	–	0.558	0.546	0.535	0.533	0.530	0.523	0.509	0.473	0.468	0.475	0.468	0.454	0.442	Slovenia
Spain	0.216	0.211	0.215	0.203	0.211	0.216	0.199	0.203	0.196	0.202	0.196	0.184	0.186	0.180	0.184	Spain
Sweden	0.118	0.138	0.128	0.128	0.134	0.116	0.123	0.099	0.092	0.055	0.010	0.030	0.010	0.000	0.000	Sweden
Turkey	0.543	0.557	0.556	0.543	0.558	0.561	0.564	0.556	0.549	0.562	0.558	0.563	0.544	0.539	0.520	Turkey
United Kingdom	0.472	0.483	0.474	0.465	0.459	0.453	0.457	0.437	0.424	0.407	0.384	0.370	0.351	0.332	0.302	United Kingdom
United States	0.525	0.533	0.512	0.492	0.473	0.456	0.411	0.353	0.258	0.170	0.090	0.120	0.111	0.075	0.000	United States
Average	0.444	0.446	0.444	0.443	0.435	0.427	0.422	0.405	0.382	0.359	0.335	0.329	0.317	0.308	0.290	Average

Table 2 – Efficiency assessment with desirable-output-oriented directional distance function (in bold optimal γ^* values below 0.1)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	
Australia	0.500	0.531	0.494	0.458	0.423	0.350	0.314	0.252	0.174	0.109	0.077	0.000	0.015	0.022	0.000	Australia
Austria	0.318	0.300	0.222	0.224	0.192	0.216	0.218	0.200	0.155	0.117	0.086	0.094	0.089	0.083	0.060	Austria
Belgium	0.500	0.476	0.453	0.460	0.419	0.395	0.390	0.355	0.334	0.300	0.252	0.236	0.220	0.217	0.188	Belgium
Canada	0.507	0.576	0.570	0.559	0.490	0.454	0.424	0.364	0.322	0.254	0.168	0.181	0.158	0.115	0.098	Canada
Czech Republic	7.970	9.499	9.912	10.019	9.808	9.178	8.778	8.821	8.854	8.518	8.292	8.084	7.942	7.767	7.371	Czech Republic
Denmark	0.208	0.236	0.228	0.251	0.210	0.184	0.115	0.135	0.120	0.101	0.074	0.069	0.069	0.061	0.051	Denmark
Finland	0.195	0.263	0.335	0.353	0.333	0.294	0.262	0.213	0.133	0.125	0.068	0.064	0.057	0.006	0.000	Finland
France	0.419	0.430	0.409	0.428	0.397	0.383	0.384	0.350	0.305	0.267	0.226	0.210	0.204	0.198	0.177	France
Germany	0.538	0.444	0.410	0.413	0.372	0.351	0.340	0.315	0.275	0.247	0.206	0.194	0.191	0.195	0.177	Germany
Greece	2.319	2.231	2.238	2.310	2.295	2.258	2.208	2.143	2.077	1.978	1.888	1.760	1.669	1.556	1.456	Greece
Hungary	7.336	7.900	7.354	7.345	7.051	6.907	6.926	6.410	5.937	5.589	5.095	4.943	4.599	4.471	4.159	Hungary
Iceland	0.415	0.436	0.503	0.498	0.463	0.476	0.421	0.367	0.306	0.266	0.231	0.200	0.224	0.201	0.126	Iceland
Ireland	1.194	1.146	1.076	1.050	0.958	0.819	0.664	0.447	0.298	0.170	0.069	0.000	0.000	0.010	0.000	Ireland
Italy	0.106	0.098	0.095	0.103	0.076	0.090	0.078	0.068	0.070	0.052	0.017	0.000	0.001	0.014	0.033	Italy
Japan	0.069	0.056	0.056	0.068	0.091	0.078	0.063	0.054	0.062	0.072	0.049	0.033	0.040	0.000	0.000	Japan
Latvia	10.201	11.456	15.436	15.088	12.629	10.848	10.578	9.006	7.845	6.594	5.419	5.477	4.988	4.520	4.107	Latvia
Netherlands	0.703	0.675	0.663	0.662	0.626	0.587	0.549	0.502	0.446	0.402	0.363	0.351	0.358	0.366	0.351	Netherlands
New Zealand	1.549	1.651	1.638	1.540	1.442	1.376	1.321	1.288	1.304	1.198	1.150	1.040	0.983	0.874	0.844	New Zealand
Norway	0.368	0.338	0.315	0.289	0.239	0.203	0.161	0.113	0.088	0.073	0.058	0.033	0.000	0.020	0.000	Norway
Poland	19.144	20.527	19.952	19.331	18.377	17.123	16.169	15.091	13.826	13.108	12.374	12.246	12.016	11.560	10.902	Poland
Portugal	0.979	0.949	0.887	1.025	1.079	1.045	0.997	1.002	1.007	0.880	0.963	0.981	0.854	1.005	0.926	Portugal
Slovakia	8.478	9.797	10.411	10.122	9.171	8.703	8.227	7.825	7.259	7.119	6.946	7.141	6.575	6.268	5.860	Slovakia
Slovenia	–	–	2.520	2.408	2.301	2.282	2.252	2.184	2.075	1.798	1.761	1.760	1.688	1.618	1.497	Slovenia
Spain	0.550	0.534	0.546	0.508	0.534	0.551	0.495	0.510	0.487	0.506	0.488	0.450	0.455	0.439	0.450	Spain
Sweden	0.236	0.276	0.273	0.283	0.266	0.227	0.218	0.192	0.164	0.110	0.020	0.061	0.021	0.000	0.000	Sweden
Turkey	2.378	2.518	2.507	2.375	2.523	2.553	2.584	2.505	2.435	2.569	2.527	2.571	2.385	2.342	2.167	Turkey
United Kingdom	1.012	1.046	1.053	1.016	0.941	0.896	0.850	0.803	0.754	0.713	0.652	0.621	0.597	0.562	0.518	United Kingdom
United States	0.310	0.343	0.312	0.274	0.241	0.217	0.141	0.119	0.088	0.060	0.000	0.052	0.053	0.036	0.000	United States
Average	2.537	2.768	2.888	2.838	2.641	2.466	2.362	2.201	2.043	1.903	1.769	1.745	1.659	1.590	1.483	Average

lower levels of the undesirable outputs. The data used in model (10) are, thus, the same P , GHG and PE targets used in model (9) plus the maximum GDP (labelled GDP*) found by model (9).

Also, although model (8) concentrates on the subset of undesirable outputs and therefore reminds of the output sub-vector measure of technical efficiency, one difference is that the reduction of the undesirable outputs in model (10) is computed from an operating point computed by model (9) and which normally would not coincide with any of the observed operating points. Another difference is that the aim of model (10) is to project the operating point on the Efficient Frontier and not the computation of any (sub-vector) measure of technical efficiency.

2.3. GHG minimization

The third model we formulate aims at minimizing GHG given the values of the other three variables. Thus, P and GDP are known and either PE or CF is fixed. Again, we have more than one variant of the model. For the sake of simplicity, let us assume that the absolute value of primary energy is fixed at level PE. The other variant of the model is formulated in Appendix A. The objective of this model is to find the minimum GHG emissions level compatible with fixed values of P , GDP and PE. The model can be formulated as

$$\begin{aligned}
 &\text{Min} \quad \text{GHG} \\
 &\text{s.t.} \\
 &\sum_{j=1}^N \lambda_j P_j \leq P \\
 &\sum_{j=1}^N \lambda_j \text{GDP}_j \geq \text{GDP} \\
 &\sum_{j=1}^N \lambda_j \text{PE}_j = \text{PE} \\
 &\sum_{j=1}^N \lambda_j \text{GHG}_j = \text{GHG} \\
 &\lambda_j \geq 0 \quad \forall j \quad \text{GHG} \geq 0.
 \end{aligned} \tag{11}$$

3. Illustration of the proposed approach

In this section we will illustrate the proposed approach with the US. The data sample used corresponds to most of the countries in the Annex B of the Kyoto Protocol (Belarus, Bulgaria, Croatia, Estonia, Lithuania, Liechtenstein, Monaco, Romania and Ukraine were omitted due to data unavailability and Luxemburg and Switzerland because of their special characteristics of large weight of financial sector). Population data were obtained from the United Nations Population Division (UNPD, 2004). The GDP data (at market prices, 1990 prices, US\$) were obtained from United Nations Statistics Division (UNSD, 2007). The PE data correspond to the total energy production (in Million tonnes of oil equivalent Mtoe) in the OECD Factbook (OECD, 2007). Finally, the emissions data correspond to the GHG total without LULUCF (in Gg CO₂-eq) from submitted National Communications (UNFCCC, 2007).

Since the data sample included several years (namely from 1990 through 2004) an inter-temporal approach has been adopted (Tulkens and Vanden Weckaut 1995).

Table 1 shows the results of the efficiency assessment of the data sample carried out with model (6). Shown in bold type are those observations whose optimal β value is below 0.1. Note that just a few observations (mainly corresponding to the most recent years) have a zero score, namely Denmark, Ireland, Italy, Japan, Norway, Sweden and the USA. For the rest of observations the model found possible a simultaneous increase of GDP and decrease of both energy supply and GHG emissions. These results are consistent with those found in other studies (e.g. Ray and Mukherjee, 2007). Note also that the average of the optimal β values show a slow but consistent efficiency increase along these years.

Tables 2 and 3 show the corresponding optimal objective function values for models (7) and (8) respectively. Note how the observations corresponding to USA in recent years have low γ^* values and large α^* values. This seems to imply that these observations are located in the vicinity of a point such as B in Fig. 1, in which GDP can hardly be increased (if at all) maintaining PE and GHG constant while PE and GHG can be significantly decreased without GDP loss. Note that, in average and assuming efficiency, countries can more than duplicate their current GDP or, alternatively, reduce their PE and GHG by approximately 45%. The trend in efficiency increase mentioned above can be observed again in both tables.

Fig. 3 shows the evolution (using 1990 as base) of GDP, EI, CI, CF and GHG for the US. The time horizon is from 1990 through 2012. Since GHG emissions level is known only up to 2004, the projections for subsequent years correspond to estimations. Estimations of GDP, PE and CO₂ emissions for 2010 and 2015 were obtained from the Reference Case Projections in the International Energy Outlook 2007 (US Department of Energy, 2007). These estimations include the 2012 CI target assumed by the Bush Administration within its Climate Change Initiative as an alternative to its non-ratification of the Kyoto Protocol. Note that in this period GHG emissions would increase around 20% but since GDP would increase much more (close to 100%), in the end CI would decrease around 35% and EI even more (around 45%). Note that the 2012 CI target is within reach just following, in a Business As Usual sense, the trend observed in the last fifteen years. Therefore, it does not seem that the USA would need to make any extraordinary effort to attain this goal. On the contrary, reducing GHG to 93% of 1990 level as stipulated by the Kyoto Protocol would require a drastic change from current policies and trends.

For the 2012 analysis that is reported below several alternative values of CI around that target are considered. Similarly, several different alternative target values for CI and CF in year 2012 are considered. For the population data, the medium growth projection for 2012 (namely 317.768 million inhabitants) is used. Fig. 4 shows the results of model 9a (panel a of the figure) and 9c (panel b of the figure). The graphs show the estimation of maximum GDP for the specified values of GHG, CI and EI (all three indexed with reference to year 1990). The corresponding numerical values are shown in Tables 4 and 5 in Appendix B. Note that certain combinations of high GHG emissions and low EI are infeasible, i.e. from the observed data it cannot be empirically assumed the feasibility of

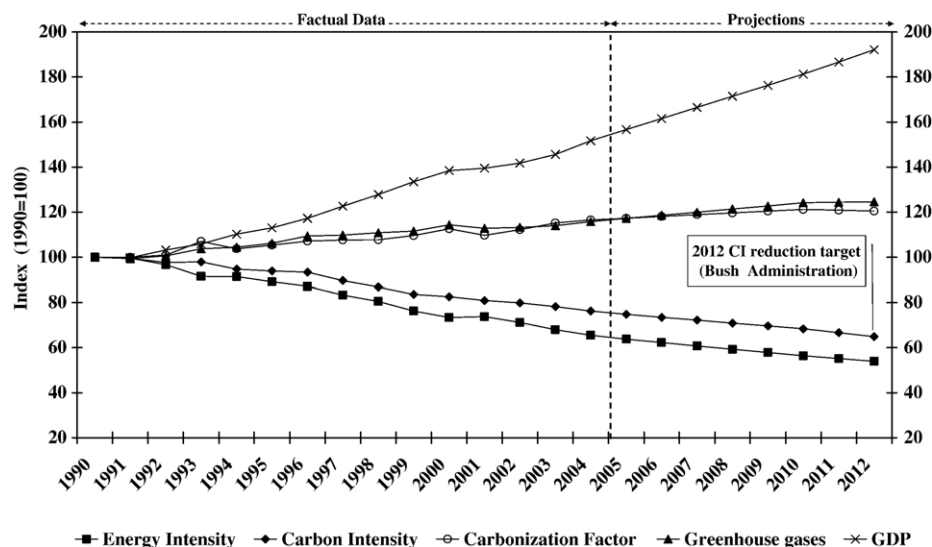
Table 3 – Efficiency assessment with undesirable-output-oriented directional distance function (in bold optimal α^* values below 0.1)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	
Australia	0.819	0.823	0.821	0.816	0.808	0.810	0.805	0.804	0.805	0.798	0.805	0.806	0.802	0.794	0.794	Australia
Austria	0.241	0.249	0.182	0.183	0.161	0.177	0.182	0.167	0.134	0.105	0.079	0.105	0.113	0.144	0.117	Austria
Belgium	0.484	0.482	0.467	0.464	0.459	0.453	0.462	0.424	0.427	0.395	0.372	0.360	0.345	0.350	0.335	Belgium
Canada	0.785	0.792	0.796	0.795	0.792	0.792	0.794	0.790	0.783	0.775	0.772	0.766	0.761	0.766	0.760	Canada
Czech Republic	0.942	0.945	0.940	0.939	0.934	0.930	0.928	0.930	0.926	0.920	0.921	0.920	0.917	0.917	0.914	Czech Republic
Denmark	0.345	0.427	0.393	0.417	0.417	0.390	0.460	0.424	0.394	0.399	0.396	0.393	0.400	0.419	0.406	Denmark
Finland	0.369	0.385	0.410	0.425	0.449	0.413	0.429	0.403	0.332	0.331	0.221	0.224	0.211	0.145	0.000	Finland
France	0.319	0.342	0.326	0.319	0.296	0.296	0.308	0.282	0.263	0.228	0.198	0.186	0.176	0.176	0.160	France
Germany	0.535	0.485	0.452	0.442	0.414	0.400	0.402	0.376	0.343	0.315	0.291	0.288	0.278	0.283	0.268	Germany
Greece	0.704	0.692	0.693	0.698	0.699	0.696	0.696	0.698	0.700	0.688	0.687	0.674	0.662	0.654	0.641	Greece
Hungary	0.880	0.888	0.880	0.880	0.876	0.874	0.874	0.865	0.856	0.848	0.836	0.832	0.821	0.817	0.806	Hungary
Iceland	0.550	0.539	0.547	0.558	0.539	0.548	0.540	0.541	0.527	0.530	0.500	0.474	0.482	0.454	0.339	Iceland
Ireland	0.661	0.650	0.637	0.636	0.627	0.607	0.574	0.509	0.420	0.364	0.255	0.124	0.000	0.043	0.000	Ireland
Italy	0.096	0.089	0.087	0.093	0.071	0.083	0.072	0.064	0.065	0.049	0.016	0.000	0.001	0.022	0.036	Italy
Japan	0.065	0.053	0.053	0.063	0.099	0.081	0.075	0.064	0.058	0.067	0.052	0.032	0.041	0.000	0.000	Japan
Latvia	0.925	0.925	0.939	0.938	0.927	0.916	0.914	0.900	0.887	0.868	0.844	0.846	0.833	0.819	0.804	Latvia
Netherlands	0.602	0.614	0.608	0.614	0.597	0.588	0.602	0.560	0.535	0.487	0.461	0.469	0.465	0.461	0.485	Netherlands
New Zealand	0.779	0.786	0.789	0.775	0.763	0.755	0.756	0.762	0.754	0.749	0.745	0.741	0.733	0.720	0.708	New Zealand
Norway	0.413	0.346	0.268	0.279	0.261	0.199	0.184	0.131	0.126	0.123	0.058	0.068	0.000	0.020	0.000	Norway
Poland	0.958	0.960	0.958	0.957	0.955	0.951	0.949	0.945	0.937	0.934	0.928	0.927	0.924	0.923	0.919	Poland
Portugal	0.495	0.487	0.470	0.506	0.519	0.511	0.499	0.500	0.502	0.468	0.491	0.495	0.460	0.501	0.481	Portugal
Slovakia	0.915	0.916	0.916	0.910	0.902	0.897	0.892	0.887	0.879	0.877	0.874	0.877	0.868	0.862	0.854	Slovakia
Slovenia	–	–	0.716	0.707	0.697	0.695	0.692	0.687	0.675	0.643	0.638	0.644	0.638	0.625	0.613	Slovenia
Spain	0.355	0.348	0.353	0.337	0.348	0.355	0.331	0.338	0.328	0.336	0.328	0.310	0.313	0.305	0.311	Spain
Sweden	0.211	0.243	0.228	0.227	0.236	0.207	0.219	0.180	0.169	0.105	0.019	0.058	0.020	0.000	0.000	Sweden
Turkey	0.704	0.716	0.715	0.704	0.716	0.719	0.721	0.715	0.709	0.720	0.716	0.720	0.705	0.701	0.684	Turkey
United Kingdom	0.641	0.651	0.644	0.635	0.629	0.624	0.627	0.608	0.595	0.579	0.555	0.540	0.519	0.499	0.463	United Kingdom
United States	0.735	0.734	0.728	0.723	0.717	0.713	0.709	0.697	0.687	0.673	0.666	0.662	0.655	0.645	0.634	United States
Average	0.575	0.577	0.572	0.573	0.568	0.560	0.561	0.545	0.529	0.513	0.490	0.484	0.469	0.467	0.448	Average

operation points with these combinations of values. Fig. 5 shows the same results as Fig. 4b but using EI as x-axis. Note that the results show that GDP increases with EI and decreases with GHG and CI. The latter is evidence of the present production of excessive (i.e. more than required) GHG undesirable output. Fig. 5 shows the maximum GDP obtained using model (9), which considers upper bounds on GHG. That corresponds to top-most curve and it means that significantly higher GDP could be achieved if GHG emissions were reduced

below the specified levels and, on the contrary, increasing GHG would lead to lower instead of GDP.

Figs. 6 and 7 show the results of models 11 and 11a respectively that estimate the minimum GHG level (measured with reference to 1990) compatible with specified GDP levels (transformed into equivalent Compound Annual Growth Rates, CAGR, in the period 2006–2012) and EI or CF respectively. The corresponding numerical values are shown in Tables 6 and 7 in Appendix B. As expected, the higher the GDP growth,

**Fig. 3 – Evolution of GDP, CI, EI, GHG and CF for USA during period 1990–2012.**

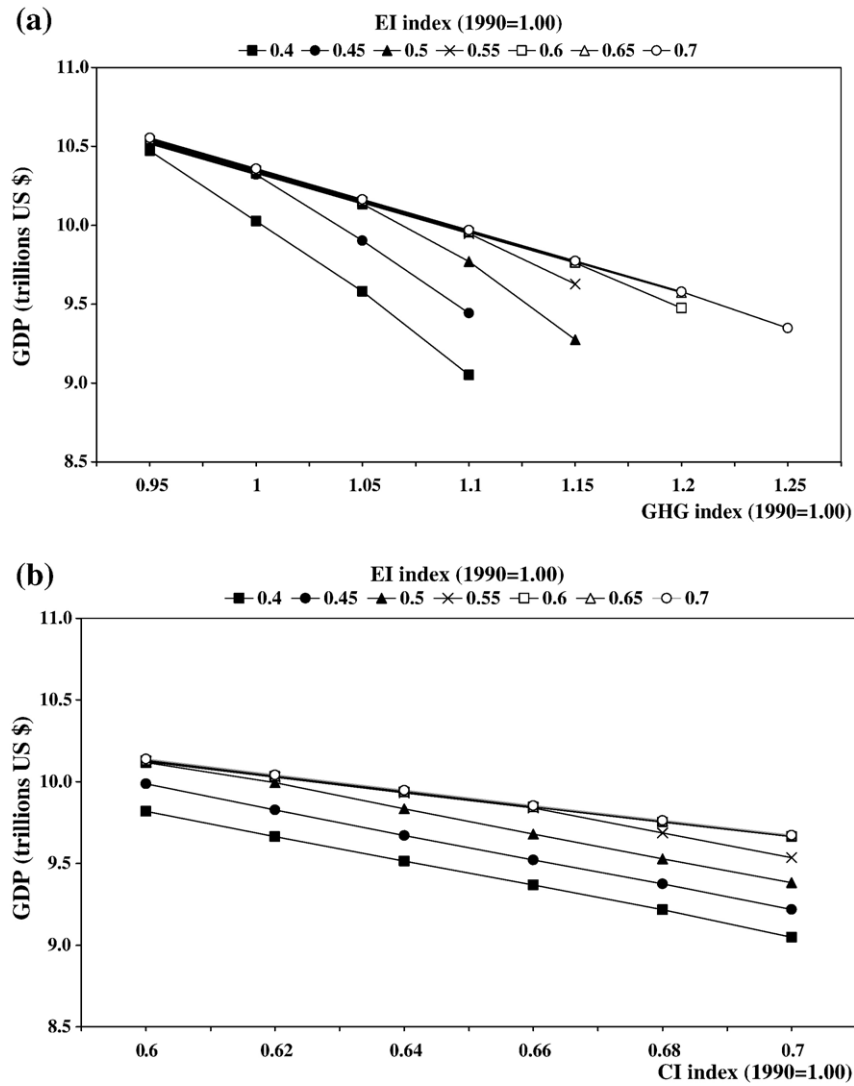


Fig. 4–Maximum GDP for specified levels of GHG and EI (panel a) and CI and EI (panel b).

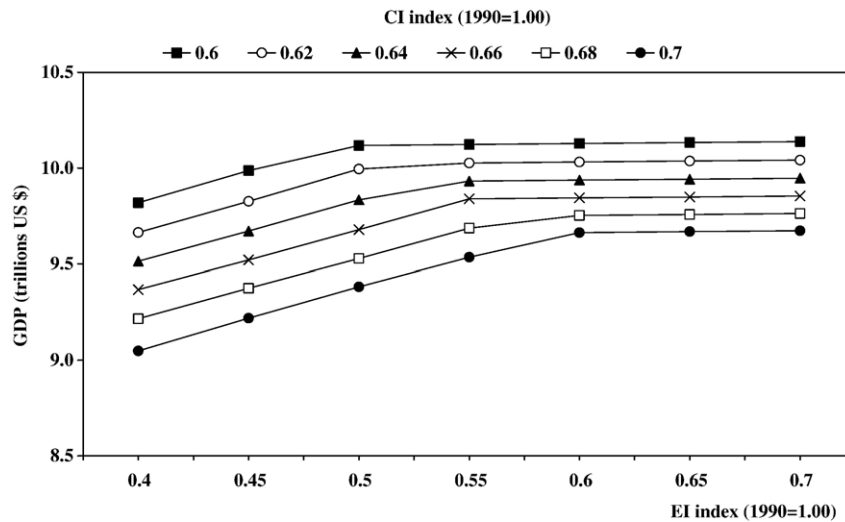


Fig. 5–Maximum GDP for specified levels of EI and CI.

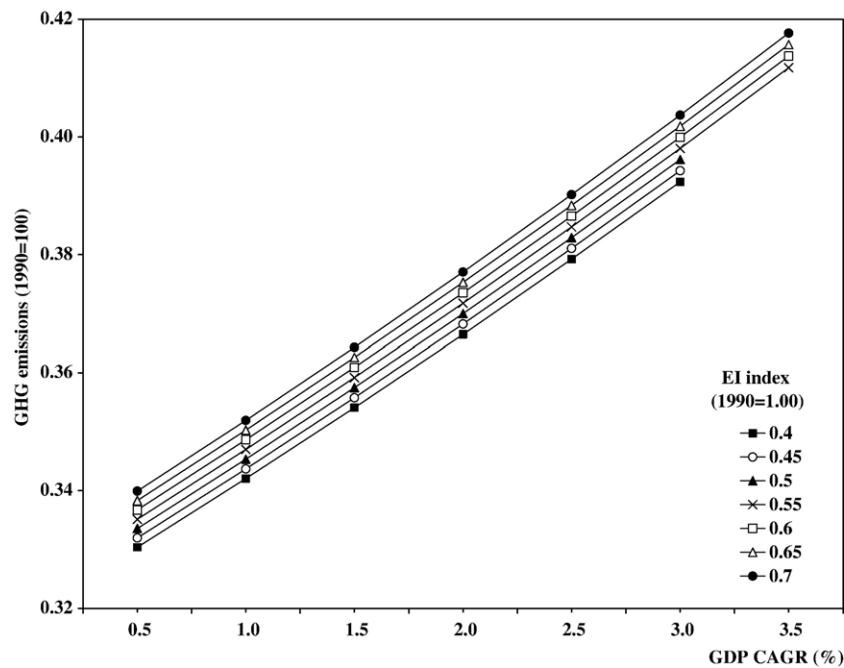


Fig. 6 – Minimum GHG compatible with specified levels of GDP and EI.

the higher the GHG emissions. What is remarkable is the estimation that significant reductions from current GHG levels (for example to a level around 40% of those of 1990) are compatible with GDP CAGR above 3%. This would require EI values slightly below the value currently projected for 2012. A GDP CAGR of 3% would also be compatible with a smaller GHG reduction (to a level around 70% of those of 1990) if CF were lowered to 50% of 1990 values, a significant reduction from the value currently projected for 2012.

4. Summary and conclusions

In this paper we propose a number of non-parametric, LP-based models to estimate the relationship among Population, GDP, PE

and GHG emissions. In one of the models, maximum GDP levels are obtained as a function of PE (or EI) and GHG (or CI). Other models proposed allow the estimation of the lowest GHG emissions level compatible with specified levels of GDP and either PE or EI or CF. Note that all these models assume that countries perform according to observed best practice. Also, a model for efficiency assessment using directional distance function has been formulated. The numerical results show a steady efficiency increase in average along the period 1990–2004.

As for the USA, the results of the proposed models show that: a) reasonable GDP growth rates are compatible with significant reductions (from current levels) in GHG emission levels, and b) higher levels of GDP could be attained if GHG consumption were reduced instead of increased. Both assertions are contingent, of course, on the assumption of efficient behaviour.

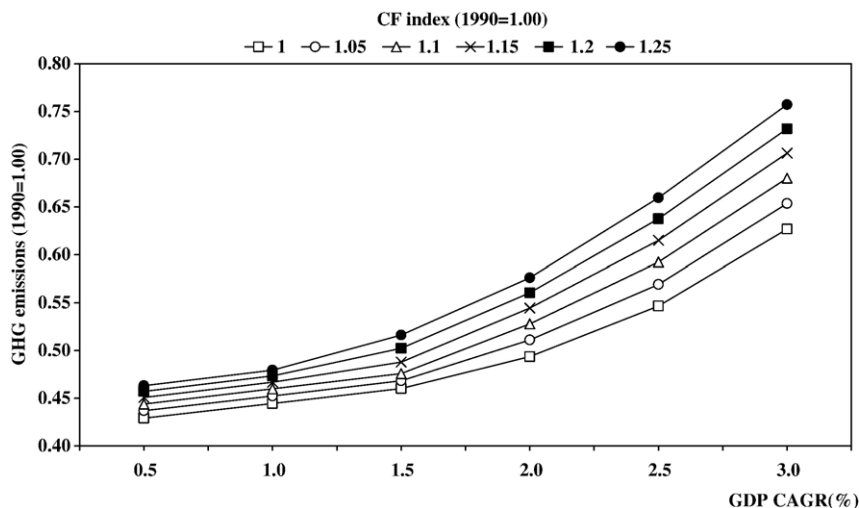


Fig. 7 – Minimum GHG compatible with specified levels of GDP and CF.

Appendix A.

Variants of model (9)

a) With EI as surrogate of PE

$$\begin{aligned}
 &\text{Max} \quad \text{GDP} \\
 &\text{s.t.} \\
 &\sum_{j=1}^N \lambda_j P_j \leq P \\
 &\sum_{j=1}^N \lambda_j \text{GDP}_j \geq \text{GDP} \\
 &\sum_{j=1}^N \lambda_j \text{PE}_j = \text{GDP} \cdot \text{EI} \\
 &\sum_{j=1}^N \lambda_j \text{GHG}_j = \text{GHG} \\
 &\lambda_j \geq 0 \quad \forall j \quad \text{GDP} \geq 0.
 \end{aligned}$$

b) With CI as surrogate of GHG

$$\begin{aligned}
 &\text{Max} \quad \text{GDP} \\
 &\text{s.t.} \\
 &\sum_{j=1}^N \lambda_j P_j \leq P \\
 &\sum_{j=1}^N \lambda_j \text{GDP}_j \geq \text{GDP} \\
 &\sum_{j=1}^N \lambda_j \text{PE}_j = \text{PE} \\
 &\sum_{j=1}^N \lambda_j \text{GHG}_j = \text{GDP} \cdot \text{CI} \\
 &\lambda_j \geq 0 \quad \forall j \quad \text{GDP} \geq 0.
 \end{aligned}$$

c) With EI as surrogate of PE and CI as surrogate of GHG

$$\begin{aligned}
 &\text{Max} \quad \text{GDP} \\
 &\text{s.t.} \\
 &\sum_{j=1}^N \lambda_j P_j \leq P \\
 &\sum_{j=1}^N \lambda_j \text{GDP}_j \geq \text{GDP} \\
 &\sum_{j=1}^N \lambda_j \text{PE}_j = \text{GDP} \cdot \text{EI} \\
 &\sum_{j=1}^N \lambda_j \text{GHG}_j = \text{GDP} \cdot \text{CI} \\
 &\lambda_j \geq 0 \quad \forall j \quad \text{GDP} \geq 0.
 \end{aligned}
 \tag{9c}$$

Variant of model (11)

$$\begin{aligned}
 &\text{Min} \quad \text{GHG} \\
 &\text{s.t.} \\
 &\sum_{j=1}^N \lambda_j P_j \leq P \\
 &\sum_{j=1}^N \lambda_j \text{GDP}_j \geq \text{GDP} \\
 &\sum_{j=1}^N \lambda_j \text{PE}_j = \frac{1}{\text{CF}} \cdot \text{GHG} \\
 &\sum_{j=1}^N \lambda_j \text{GHG}_j = \text{GHG} \\
 &\lambda_j \geq 0 \quad \forall j \quad \text{GHG} \geq 0.
 \end{aligned}
 \tag{11a}$$

Appendix B

Table 4 – Maximum estimated GDP (in trillion constant 1990 US\$ market prices) for specified combinations of GHG and EI

		GHG index (1990=1.00)						
		0.95	1.00	1.05	1.10	1.15	1.20	1.25
EI index (1990=1.00)	0.40	10.47	10.03	9.58	9.05	Infeasible	Infeasible	Infeasible
	0.45	10.52	10.32	9.90	9.44	Infeasible	Infeasible	Infeasible
	0.50	10.52	10.33	10.14	9.77	9.28	Infeasible	Infeasible
	0.55	10.53	10.34	10.14	9.95	9.63	Infeasible	Infeasible
	0.60	10.54	10.34	10.15	9.96	9.76	9.48	Infeasible
	0.65	10.55	10.35	10.16	9.96	9.77	9.57	Infeasible
	0.70	10.55	10.36	10.16	9.97	9.77	9.58	9.35

Table 5 – Maximum estimated GDP (in trillion constant 1990 US\$ market prices) for specified combinations of CI and EI

		CI index (1990=1.00)					
		0.60	0.62	0.64	0.66	0.68	0.70
EI index (1990=1.00)	0.40	9.82	9.66	9.51	9.37	9.22	9.05
	0.45	9.99	9.83	9.67	9.52	9.38	9.22
	0.50	10.12	9.99	9.83	9.68	9.53	9.38
	0.55	10.12	10.03	9.93	9.84	9.69	9.54
	0.60	10.13	10.03	9.94	9.84	9.75	9.66
	0.65	10.13	10.04	9.94	9.85	9.76	9.67
	0.70	10.14	10.04	9.95	9.85	9.76	9.67

Table 6 – Minimum GHG index (1990=1.00) compatible with specified combinations of GDP CAGR and EI

		EI index (1990=1.00)					
		0.40	0.45	0.50	0.55	0.60	0.65
GDP CAGR (%)	0.5	0.33	0.33	0.33	0.34	0.34	0.34
	1.0	0.34	0.34	0.35	0.35	0.35	0.35
	1.5	0.35	0.36	0.36	0.36	0.36	0.36
	2.0	0.37	0.37	0.37	0.37	0.37	0.38
	2.5	0.38	0.38	0.38	0.38	0.39	0.39
	3.0	0.39	0.39	0.40	0.40	0.40	0.40
	3.5	Infeasible	Infeasible	Infeasible	0.41	0.41	0.42
	4.0	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible

Table 7 – Minimum GHG index (1990=1.00) compatible with specified combinations of GDP CAGR and CF

		CF index (1990=1.00)					
		0.40	0.45	0.50	0.55	0.60	0.65
GDP CAGR (%)	0.5	0.43	0.44	0.44	0.45	0.46	0.43
	1.0	0.44	0.45	0.46	0.47	0.47	0.44
	1.5	0.46	0.47	0.48	0.49	0.50	0.46
	2.0	0.49	0.51	0.53	0.54	0.56	0.49
	2.5	0.55	0.57	0.59	0.62	0.64	0.55
	3.0	0.63	0.65	0.68	0.71	0.73	0.63
	3.5	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
	4.0	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible

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